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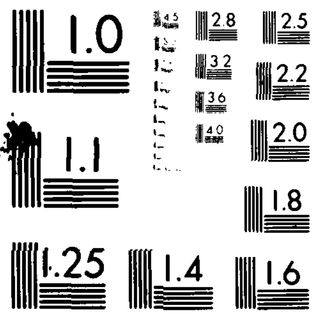

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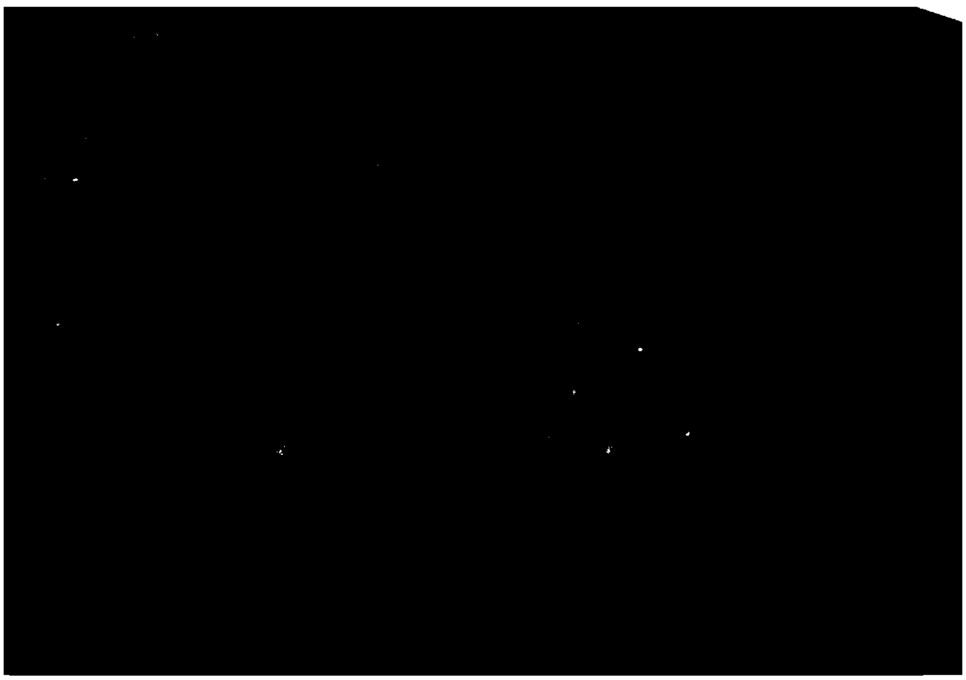

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LNG CARRIER UNDERWATER NOISE STUDY FOR BAFFIN BAY

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RESEARCH AND DEVELOPMENT BRANCH
DEPARTMENT OF NATIONAL DEFENCE
CANADA

ABSTRACT

Large powerful liquid natural gas carriers may soon ply Arctic waters year round. Concern has been expressed over the impact the resulting noise will have on Arctic marine life. This study includes estimates of LNG carrier radiated noise source levels and resulting sound levels at a given distance from the ship for a number of operating conditions. Measurements of sound propagation and ambient noise conditions in Baffin Bay are used to estimate the ship noise levels in relation to the summertime noise background.

RESUME

De gros méthaniers puissants pourraient bientôt sillonner les eaux de l'Arctique à l'année longue. Cette perspective a soulevé des inquiétudes au sujet des effets du bruit sur les animaux marins. La présente étude comprend des évaluations de l'intensité du bruit émis par les transporteurs du GNL et entendu à une distance donnée de ceux-ci, dans diverses conditions. Les mesures de propagation des sons et d'intensité du bruit ambiant dans la baie de Baffin sont utilisées pour calculer le bruit des navires par rapport au fond sonore estival.

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1. INTRODUCTION

1.1 Background

The Arctic Pilot Project of Petro-Canada is designed to produce and liquify natural gas in the Canadian Arctic and to move it to eastern Canadian markets in ice-breaking ships.

The Arctic gas will be shipped in carriers designed to exceed the requirements of Class 7 ice-breakers. Initially, two ships will be constructed. Each will have a length of 375 m, beam of 43 m and displacement of 140,000 metric tons. The propulsion system for the LNG carriers will consist of three fixed pitch propellers, one located on the ship centre, and two on wing mounts, each powered by separate turbo-electric power systems capable of delivering 50 Megawatts (MW). The propellers will be 8 m in diameter.

The proposed shipping routes, shown in Figure 1, will follow the traditional North-West Passage, and should allow the delivery of gas to eastern Canadian markets year-round. The shipping route passes through international waters in the area of the Davis Strait and Baffin Bay.

Discussions have been underway with the Danish Ministry for Greenland since August 1977, concerning the project and its possible impact on the physical and human environments of West Greenland. Recently the Danes have raised concerns over the impact of the noise generated by the LNG carriers on the sea mammal life off the Greenland coast. In particular, the noise may interfere with whale communications, navigation, and echo location of food. Because the economy of West Greenland and the livelihood of the Inuit who live there is dependent upon the harvest of mammals from the area, factors which may produce an imbalance in the enviroment may have detrimental influence on the inhabitants of West Greenland.

In its efforts to assess the potential impact of the LNG carrier noise levels on the undersea environment, Petro-Canada consulted the Defence Research Establishment Atlantic (DREA) regarding the noise levels likely to be produced by the ships, and their effect on ambient noise conditions in Baffin Bay. As DREA has considerable experience in research pertaining to ship noise generation, sound propagation, and ambient noise levels in waters of interest to Canada, the problem was of some interest. In addition, the ensuing data from full scale trials, which would be made available to DREA if the ships are built, would be an important addition to its data base of propeller noise and performance. As a result, DREA undertook to carry out the following analyses.

1.2 Approach

The DREA approach to the problem follows the classical lines of environmental noise studies. First hydrodynamic and hydro-acoustic methods are used to estimate the acoustic source levels of the LNG carrier. The results from the estimation procedures are compared with full scale data from existing ships to verify their accuracy. Given the expected source levels, the results of propagation loss experiments are applied to determine the local spectrum levels at a specific distance from the ship. These levels are compared with ambient noise levels measured in the Baffin Bay region during the summer period. The result is an estimate of the upper bound of the LNG carrier noise for various speeds, which can be compared with ambient noise levels some distance from the ship.

2. ESTIMATION OF SHIP RADIATED NOISE LEVELS

Surface ship radiated noise is generated by various components of the ship's systems. The main ones have been consistently identified as machinery and propellers. Once the propellers begin to cavitate, their acoustic output generally dominates the ship noise spectrum. The shape of a typical spectrum which could be produced by a cavitating propeller is shown in Figure 2. Here discrete tones are superimposed on a broad-band hump-shaped spectrum which falls off with a slope of -6 dB/Octave between 40-300 Hz and 10 kHz. Above 10 kHz, the slope of the spectrum decreases to -3 dB/Octave to 50 kHz. The discrete tones are caused by periodic fluctuations of the cavitation on the propeller blades, while the broad-band portion of the spectrum is caused by irregular phenomena of the cavitation such as bubble collapse and sheet cavity separation.

2.1 Estimation of the Broad-Band Levels

Theoretical foundations of hydro-acoustic noise indicate that propeller cavitation noise power should be proportional to the total number of blades cavitating, the propeller diameter, and the propeller tip speed, the dependence on tip speed being the strongest[1]. Ship size or tonnage would not nesessarily enter the equation, except that larger ships require more thrust, and hence would be fitted with larger and perhaps a greater number of propellers. Examination of data[1] shows a clear trend with tip speed and number of blades. A relationship for estimating the overall noise levels from ships over 100 m in length, operating in calm, open ocean conditions can be represented by:

$$L'_s = 175 + 60 \log \frac{U_t}{25} + 10 \log \frac{B}{4} \tag{1}$$

where U_t is the propeller tip speed, m/s

B is the number of blades

L'_s is the overall noise level in dB re 1μPa (also dB//1μPa) in a bandwidth from 100 Hz to 10 kHz.

This relationship which may be considered valid over a range of tip speeds from 15 to 50 m/s, gives the total energy produced by the cavitating propeller in the 100 Hz to 10 kHz band.

Ship noise is usually presented in terms of equivalent spectrum levels as shown in Figure 2. To convert the overall level to a spectrum level, certain conditions must be set regarding the shape of the spectrum. We assume that the spectrum is flat from 0 Hz to 100 Hz; thereafter it falls off at -6 dB/Octave. This spectrum shape is shown in Figure 3. The overall level from 0 to 10 kHz is then given by

$$L_s = 10 \log \left(\ell_o \int_0^{100} df + 10^4 \ell_o \int_{100}^{10,000} \frac{1}{f^2} df\right) \tag{2}$$

where $$L'_s = 10 \log \left(10^4 \ell_o \int_{100}^{10,000} \frac{1}{f^2} df\right)$$

$$L_o = L'_s - 20 \tag{3}$$

where ℓ_o is the mean-square acoustic pressure of the flat portion of the spectrum in μPa^2

L_o is the level of the flat portion of the spectrum in dB re 1μPa

f is frequency in Hz.

With this technique it is possible to calculate the spectrum level vs frequency given an estimated overall level.

A method to predict the propeller noise spectrum level at a specific frequency for propellers operating in heavily loaded conditions is given by Brown[2]. This relationship is as follows.

$$L_f = 163 + 40 \log D + 30 \log N + 10 \log B - 20 \log f + 10 \log \frac{A_c}{A_D} \tag{4}$$

where L_f is the spectrum level at frequency f in dB re $1\mu Pa$

D is the propeller diameter in metres

N is the revolution rate per second

B is the number of blades

f is the frequency in Hz

A_c is the area of the blades covered by cavitation in square metres

A_D is the total propeller disc area in square metres

This formula applies in the mid-band frequency range where the spectrum level is dropping at -6 dB/Octave. Below 100 Hz the spectrum is assumed flat, having a level equal to that predicted at 100 Hz.

The first method was verified by comparing its results with sound range measurements from naval vessels, range corrected open ocean measurements of a large commercial ship measured from a DREA underwater acoustic research ship, and commercial ship noise data obtained from the open literature[3]. The displacements of these test ships ranged from about 4,000 to approximately 310,000 metric tons. To test the validity of Equation 4, a comparison was performed with a naval propeller operating at an off-design heavily loaded condition. This comparison showed that Equation 4 should be used with a value of $A_c/A_D = 1.0$

Because both methods predict a flat spectrum below 100 Hz, it could be expected that they might underestimate the noise level in the broadband hump region near 100 Hz and overestimate the level at lower frequencies. However, the combinations of Equations 1 and 3 underestimated the measured noise levels below 100 Hz by approximately 2 dB. This situation probably arose because of the presence in the actual signal of blade rate and harmonic frequencies, whose contribution was not included in the broadband noise portion of the analysis. Above 100 Hz the theory was higher than the measured data. The discrepancy ranged from 6 to 11 dB. Because the results using Equations 1 and 3 were significantly higher than the measured data, the levels were reduced by 3 dB, over the entire spectrum. This method gave the best agreement with the ship noise data at DREA.

For the heavily loaded, off-design propeller, the theory (Equation 4) was higher than measured data by about 6 dB up to 1000 Hz. Above this frequency the agreement was within 4 dB.

With the results of this comparison it is appropriate to employ Equations 1 and 3 to estimate open ocean noise levels, and to use Equation 4 for the ice conditions, which require high propeller loads at off-design conditions. As both approximation

methods generally over-estimate the actual radiated noise spectrum levels, the estimates presented may be considered as upper bounds.

Estimates of the broad-band radiated noise levels for six conditions were calculated for the LNG carrier using Equations 1 and 3 for the open water cases, and 4 for light and heavy ice conditions. The conditions are shown in Table 1. The results from these calculations are plotted in Figure 4.

TABLE 1: CONDITIONS FOR LNG CARRIER NOISE ESTIMATES

SHIP SPEED (kt)	CONDITION	WING PROPELLER RPM	WING PROPELLER POWER (MW)	CENTRE PROPELLER RPM	CENTRE PROPELLER POWER (MW)	TOTAL POWER (MW)
4	heavy ice	103	43.5	103	44.6	131.6
10	light ice	96	29.7	96	32.5	92.0
14.4	open water	63	4.9	58	5.1	14.8
19.5	open water	82	10.1	74	10.0	30.2
21.8	open water	93	15.1	84	14.8	45.0
26.0	open water	102	17.1	102	27.0	61.1

As expected, the spectrum levels are highest for the heavy ice condition, which produces an L_o of 178 dB re 1μPa. The light ice condition is slightly less at 175.8 dB re 1μPa while the open water levels range from 171.7 to 158.4 dB re 1μPa.

2.2 Estimation of Blade-Rate Frequencies

For a cavitating propeller, the blade-rate discrete tone and its harmonics are generated principally by the fluctuations of the cavitation volumes on the propeller blades. The frequencies of the blade-rate and its harmonics are given by the relationship

$$F = n(B \times N) \qquad (5)$$

where n is the harmonic number
B is the number of blades
N is the revolution rate per second

A method for calculating the amplitudes of the discrete tones is not yet available, but it is possible to obtain an approximate estimate of the levels by taking measured blade-rate levels from ships with comparable horsepower and stern shapes, and scaling the noise according to the power relationships of Equation 4. An analysis such as this, based on open ocean propagation loss corrected data, indicates that the level of the blade-rate frequency or any of its harmonics would not exceed 195 dB//1μPa for the 26 knot open water condition. In the heavy ice condition, where the propeller blade is expected to experience greater amounts of cavitation, the levels can be expected to increase by between 3 and 6 dB. This figure is based on sheet cavitation covering approximately 30 per cent of the blade[4]. Thus for the carrier operating in heavy ice, the maximum expected noise level with the three propellers operating would be between 198 and 201 dB//1μPa.

Because the levels of the blade rate and its harmonics are governed to a large degree by the cavity volume fluctuations, any measure to reduce these volumetric fluctuations would produce reductions in radiated noise levels at the blade-rate related frequencies. Recently, a considerable amount of attention has been directed to reducing shipboard vibration caused by the blade-rate frequency pressure fluctuations. An important aspect is to exercise care in the design of the ship's hull so that the wake in the propeller planes can be made more uniform. Also, the incorporation of skew into the propeller blade design reduces the span-wise coherence of the cavity volume fluctuations and the resulting noise. Results from full scale experiments show between 6 and 8 dB reductions in the near field pressures for cavitating propellers can be obtained by adopting skew and tip unloading in the propeller blade design,[5,6] and by improving the hull form[7].

3. SOUND PROPAGATION AND AMBIENT NOISE

3.1 Background on Noise and Sound Propagation Measurements in Baffin Bay

From 1970 through 1975 DREA made a number of acoustic measurements in eastern Canadian and West Greenland waters north of 60°N. These measurements were primarily confined to the summer months (July-September), when Baffin Bay is essentially ice-free. Short term ambient noise measurements in the frequency range 10 Hz to 2500 Hz were obtained at a number of locations as shown in Figure 5. The two symbols differentiate between data obtained from ships and from aircraft. Sound propagation measurements were also obtained by dropping explosive sources along the tracks shown in Figure 6. The signals were received at the locations shown by the circles. All ambient noise measurements are presented as measured in a 1 Hz band in decibels re $1\mu Pa/Hz^{1/2}$.

3.2 Summary of Noise Measurements

The average ambient noise levels observed in Baffin Bay were much higher than expected. In most oceans of the world, the ambient noise is generated by two major sources. In the frequency range 5-250 Hz it is generated by shipping. In the range 250 Hz to about 20,000 Hz, the noise derives primarily from agitation of the sea surface by wind or precipitation. The noise levels observed in Baffin Bay are generally higher than can be explained on the basis of these sources. The noise is also of quite a different character than typical open ocean noise. Ocean noise is largely featureless - a constant, steady roar. The noise in summertime Baffin Bay is quite non-stationary. It is full of bangs, scrapes, rumbles, and crashes. The observed noise levels change radically from instant to instant. It is believed by the authors that the major source of noise in the frequency range of 10 Hz to at least 1000 Hz is ice - even in summer.

Figure 7 shows a broad shaded area indicating the range of average noise spectrum levels that were observed in samples of about twenty minutes duration. The levels have been converted to an equivalent 1 Hz bandwidth by dividing by the bandwidth of the measurement. Similar measurements for the North Atlantic are shown in Figure 8. Both figures contain reference curves[8] showing typical spectra for shipping noise (representative of heavy and light traffic areas) and surface agitation noise (representative of sea states seven and one). In comparing Figures 7 and 8, there would appear to be little significant difference between the two; Atlantic noise is perhaps a little higher at about 50 Hz and Baffin Bay noise higher at frequencies above about 150 Hz. Average levels form only a part of the story, however.

Noise levels in the North Atlantic may range higher than the mean for periods of time in the presence of very noisy ships or in heavy rain storms. Noise levels in Baffin Bay are routinely higher than the mean even in the absence of shipping, wind, or precipitation. Figure 9 shows cumulative probability distributions for noise levels observed over a twenty minute period in Melville Bay. This figure tells us that noise levels much higher than the mean are remarkably likely. For example, in the 25-50 Hz band, spectrum levels higher than 102 dB are observed about 2% of the time. Similar distributions for a North Atlantic location are shown in Figure 10. The plots in this figure are nearly straight lines. This is indicative of a "normal" (gaussian) distribution of noise spectrum levels. The strongly curved lines in Figure 9 indicate a very non-gaussian state of affairs; loud bursts of noise are very likely.

The non-stationary, non-gaussian noise conditions observed in Baffin Bay make it very difficult to provide a complete statistical description of the noise process. The sampling techniques employed would, in most ocean areas, provide confident measures of useful noise parameters. For Baffin Bay it can only be said that the data shown in Figure 9 are typical of observations made during cruises of one to three weeks duration in each of three summers. Under such highly variable noise conditions, long term measurements - preferably extended over several seasons - would be required in order to quantify the liklihood that observations could be repeated within specified limits.

Another noise characteristic, which may be of interest, is the maximum observed short term (one to three minutes) noise spectrum level. Figure 11 shows a comparison of the maximum noise spectrum levels observed in the Atlantic and in Baffin Bay. The maximum levels for the Atlantic represent a three minute average observed in the midst of intense fishing activity. The maximum levels observed in Baffin Bay represent a 40 second period during which a small iceberg rolled over about two hundred meters from the receiving hydrophone. It is speculated that the background noise in summertime Baffin Bay arises from numerous such events distributed throughout the Bay.

Noise levels observed during other seasons of the year will depend very much upon ice and weather conditions. While winter conditions may occasionally (or perhaps usually) be quieter than summer conditions, it is probably not unreasonable to expect that during stormy weather conditions, ice generated noise levels in winter will be at least as high as those observed in summer. The only DREA non-summer measurements of noise levels were obtained in October 1970. These levels corresponded to the light traffic and sea state one reference curves shown in Figures 7 and 8.

3.3 Summary of Sound Propagation Data

The propagation loss at range R is defined as the ratio of the sound intensity at one yard from the source to the sound intensity at range R. It is usually expressed in decibels as ten times the logarithm (base 10) of this ratio.

Generally speaking, sound propagation conditions are quite "good" in Baffin Bay. That is, propagation losses are relatively low in Baffin Bay when compared to many other ocean areas. This probably accounts in part for the high noise levels observed. In comparing conditions in Baffin Bay with the North Atlantic, it could safely be said that over the deeper central part of the Bay sound propagation losses are

about equal to the lowest losses observed in the North Atlantic.

Figure 12 shows typical propagation loss results in Baffin Bay for a number of one-third octave bands spanning the frequency range 125-1000 Hz[9]. Losses for data below 125 Hz are similar to that shown for 125 Hz. These results can be reasonably well modeled (even at ranges less than 50 nautical miles) by "cylindrical spreading" (loss in decibels proportional to ten times the logarithm of range) plus a linear absorption term (loss in decibels proportional to range). In equation form, the propagation loss H in dB is approximately equal to:

$$H = C_1 + 10 \text{ Log } R + C_2 R \qquad (6)$$

where R is range. C_1 and C_2 are constants which depend upon a number of factors: depth, temperature structure, sea bottom reflection loss, surface reflection loss, water viscosity, chemical composition of the water and sound scattering within the volume of the water. Usually these constants are chosen simply to yield a best fit to experimental data. For the Baffin Bay propagation loss data appropriate constants are shown in the table below for C_1 and in Figure 13[9],

TABLE 2: BAFFIN BAY PROPAGATION LOSS CONSTANTS

FREQUENCY	C_1 R in kyd	C_1 R in Nautical Mile (NM)
31.5 Hz	62 dB	65 dB
63	61	64
125	61	64
250	62	65
500	63	66
1000	64	67

for C_2. The attenuation coefficient, C_2, may be obtained in dB per nautical mile by doubling the value shown in Figure 13 (since 1 kiloyard is approximately one-half nautical mile).

Where propagation paths include continental shelf areas, such as those found adjacent to the coasts of Greenland and Baffin Island, propagation losses increase sharply, particularly at low frequencies. These additional losses which

occur in shallow water (about 200 m deep) are a result of increased interaction with the sea bottom. Shallow water losses are quite variable, depending upon both the water depth and the nature of the bottom. Figure 14 shows propagation losses obtained at 63 Hz for the horseshoe shaped track shown in Figure 6. All points falling below the general trend correspond to parts of the track that entered shallow water. Not all points representing paths over shallow water are shown. Often the signal-to-noise ratio was too poor to obtain valid measurements. The effect can probably be approximately described by adding another term to the equation shown. The new term would be of the form + C_3R_s where R_s is the path length in shelf water.

Two sound source depths were used in the measurements, 18.3 m and 100 m. The receiver depth was 30 m or 122 m. No significant differences were noted among the various combinations of source and receiver depth.

In view of the relative stability of temperature (and hence sound velocity) structure in northern waters, little seasonal change in sound propagation conditions would be expected at low frequencies. Since the sound propagates largely in an upward refracted, surface reflected mode, the presence of a rough sea surface or ice-water interface might be expected to introduce a larger value of C_2, especially at high frequencies. The frequency at which this becomes significant will depend upon the roughness on the underside of the ice.

4. DISCUSSION OF RESULTS

Based on these estimates of the ship radiated noise, and the propagation and ambient noise information, it is possible to make reasonable predictions of the noise levels produced by the LNG carrier at specific points along the proposed shipping route.

Consider, for example, the noise level likely to be produced by the LNG carrier travelling at 26 knots in open water at a range of 100 nautical miles. If we direct our attention to the 31.5 Hz octave band, the propagation loss can be calculated, with the aid of Equation 6 to be 85 dB. Figure 4 shows that the broad band source level for this condition would be 172 dB//1μPa. Thus the noise produced by the carrier at a range of 100 nautical miles would be 172-85 = 87 dB//1μPa. Upon comparing this level with the ambient noise measured in Baffin Bay, Figure 7, we see that this level would correspond to the upper limit of the average spectrum levels observed. The maximum levels observed, Figure 11, are 25 dB higher than those expected from the carrier at this frequency. Figure 9 indicates that levels above 87 dB//1μPa at 31.5 Hz

might be expected to occur about 30 percent of the time in Baffin Bay during the summer months.

For the light ice condition, the local noise level produced at 100 nautical miles would increase to 91 dB//1μPa and for heavy ice condition to 93 dB//1μPa. Ambient levels in Baffin Bay probably exceed 91 dB//1μPa about 14 percent of the time and 93 dB//1μPa, 8 percent of the time.

The maximum local level that blade-rate discrete frequencies would produce at 100 nautical miles in heavy ice is 116 dB//1μPa (201-85 = 116). This level does not occur very frequently in the ambient noise. It is approximately equal to the maximum ambient spectrum level observed (Figure 11) and approximately 30 dB above the average ambient noise condition (Figure 7). The relative amplitude of the ambient and blade-rate noise is dependent upon the effective bandwidth in which the ambient noise is measured. For example, if the ambient noise is measured with a 1 Hz wide filter, or reduced to a 1 Hz bandwidth as done in this report, then the energy in that band would be 86 dB//1μPa. However, if the bandwidth of the filter is increased to 100 Hz, then the energy in the band would be 106 dB//1μPa (86 + 10 log 100). The difference in level between the ambient noise and the tonal in a 100 Hz wide band would be 10 dB (ie. 116 dB//1μPa for the tonal minus 106 dB//1μPa for the ambient noise). Thus when comparing ambient with tonals, knowledge of the effective bandwidth of the receiver is essential.

The levels discussed above are determined from deep water propagation results. However, as discussed in Section 3.3 and illustrated in Figure 12, the propagation loss increases sharply, especially at low frequencies, in the shallow water over a continental shelf. A maximum increase in propagation loss of 25 dB is shown in Figure 14. If the local area of interest is the continental shelf near Greenland and 19 dB is used as a typical additional loss as a result of the shelf, the total propagation loss from a carrier in deep water 100 nautical miles away would be 104 dB. The maximum local level produced by blade-rate tones in this case would be 97 dB//1μPa and the low frequency broadband spectrum level, 74 dB//1μPa.

The major results of the above discussion are summarized in Table 3.

5. CONCLUDING REMARKS

This report provides estimates of the noise levels likely to be produced by a large LNG carrier operating in Baffin Bay. Results indicate that broadband source levels as high as 178 dB//1μPa and discrete tones of levels up to 201 dB//1μPa may be produced by these ships.

Ambient noise levels in Baffin Bay tend by normal ocean standards to be high on the average. Also, the noise levels exhibit a skewed probability distribution such that higher noise levels are encountered more often than in the North Atlantic. In the shallow water near Greenland, it is expected that the highest LNG carrier broadband noise spectrum levels would be 74 dB//1μPa and the highest discrete tone levels, 97 dB//1μPa when the ship is 100 nautical miles away.

In central Baffin Bay propagation losses are low in comparison with many other ocean areas. However, shallow water over the continental shelf areas can produce large propagation losses around the perimeter of the Bay. Increases in propagation loss, over deep water conditions, of up to 25 dB may be expected.

The estimates of ship radiated noise levels presented in this report are based on full scale data and scaling relationships, and are judged to err on the high side. More accurate estimates could be obtained from a model test program which includes performance, cavitation and noise measurements. Special attention to features not addressed by the empirical model such as hull form and the use of a reduced noise propeller design would be beneficial for noise reduction.

TABLE 3: RELATION OF SHIP NOISE LEVELS TO SUMMERTIME NOISE IN BAFFIN BAY (1,2)

SHIP CONDITION	SHIP NOISE SOURCE LEVEL		SHIP LEVELS AT 100 NM		% TIME AMBIENT > SHIPLEVEL	
	Broad band (L_o)	Blade rate tonal	Broad Band	Blade Rate tonal	Broad band (3)	Blade rate tonal (4)
Open Water 26 kt	172	195	87	110	30	-
Light Ice 10 kt	176	199	91	114	14	-
Heavy Ice 4 kt	178	201	93	116	8	-

Notes: 1. Deep water results are presented above. Ship level at 100 NM should be reduced by 19 dB where sound propagates from deep water to a shelf area.

2. All levels are dB re 1μPa. Broad band levels are expressed as if measured in a 1 Hz band.

3. For the 31.5 Hz octave band.

4. Interpretation of these data require knowledge of the effective bandwidth of the receiver.

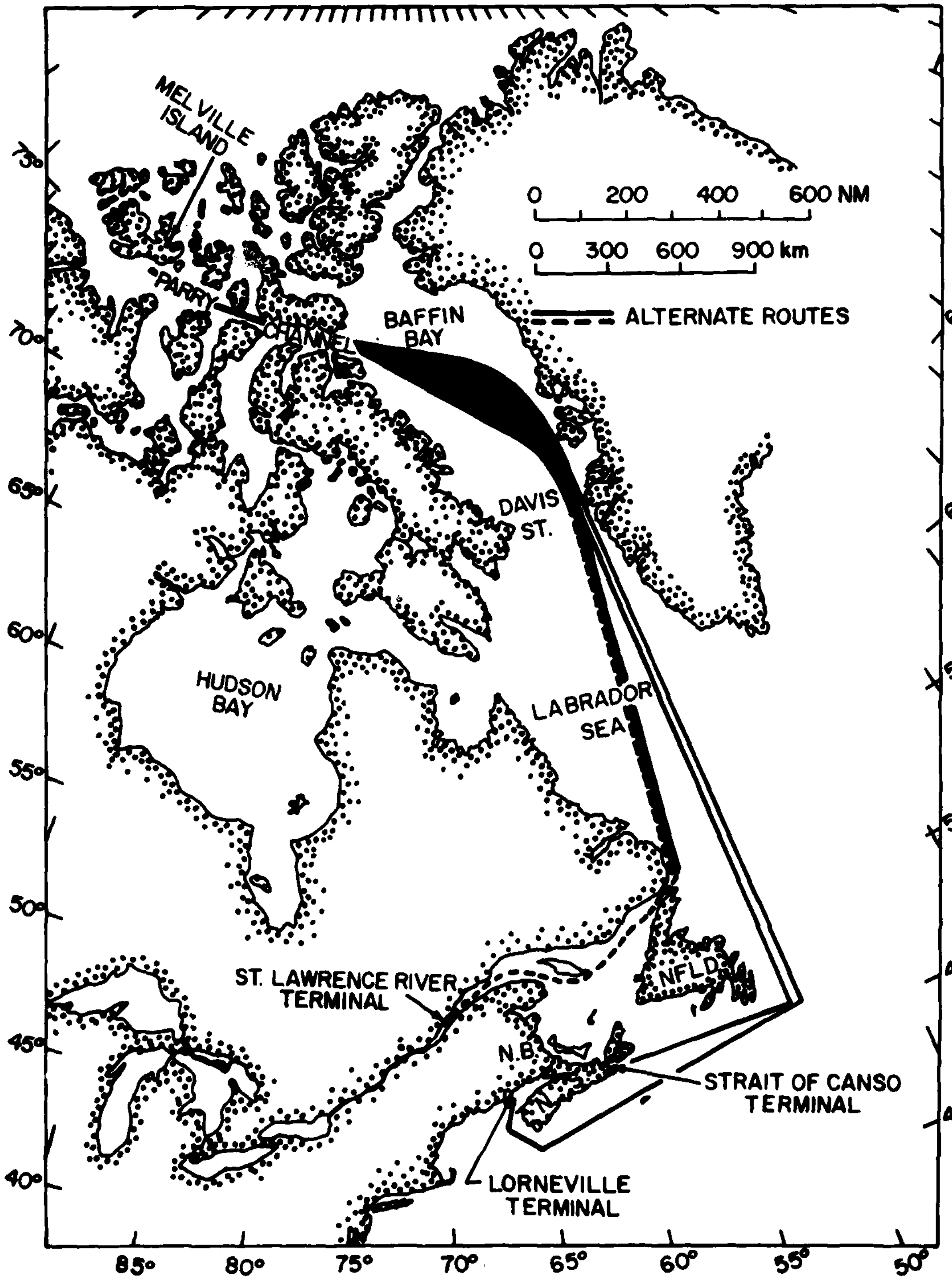

FIGURE 1: LNG CARRIER ROUTES TO MELVILLE ISLAND

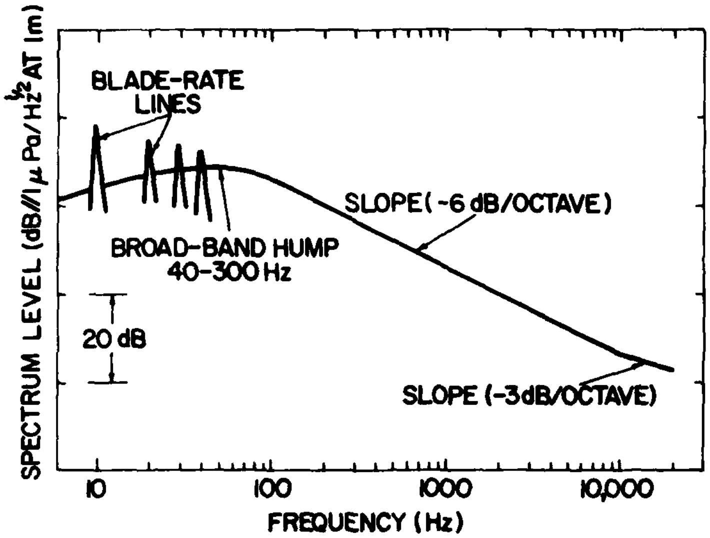

FIGURE 2: TYPICAL SOURCE SPECTRUM FROM A CAVITATION PROPELLER

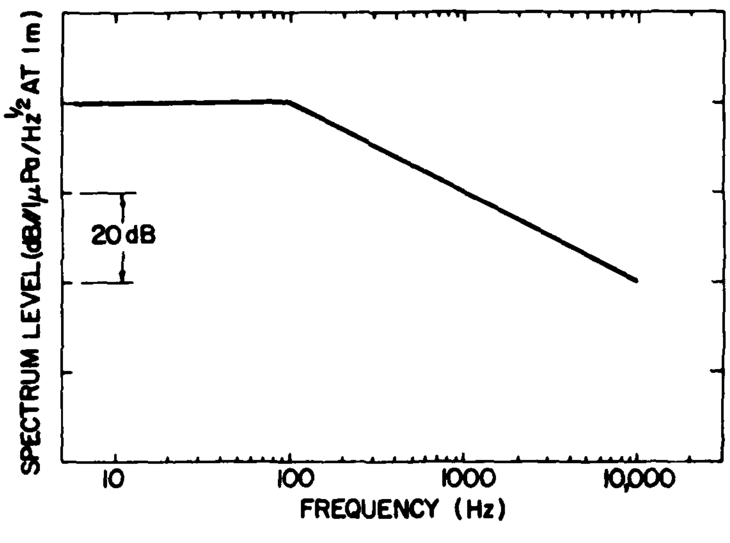

FIGURE 3: SHAPE OF ESTIMATED SPECTRUM

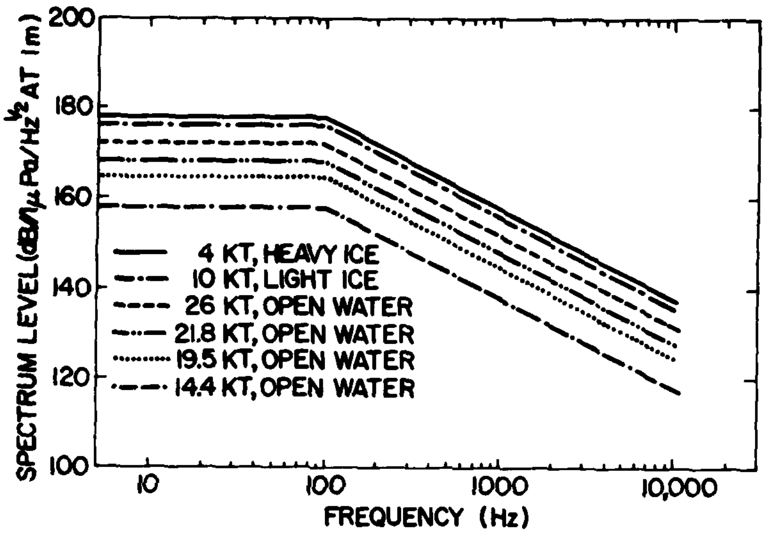

FIGURE 4: BROAD-BAND RADIATED NOISE ESTIMATES FOR LNG CARRIER

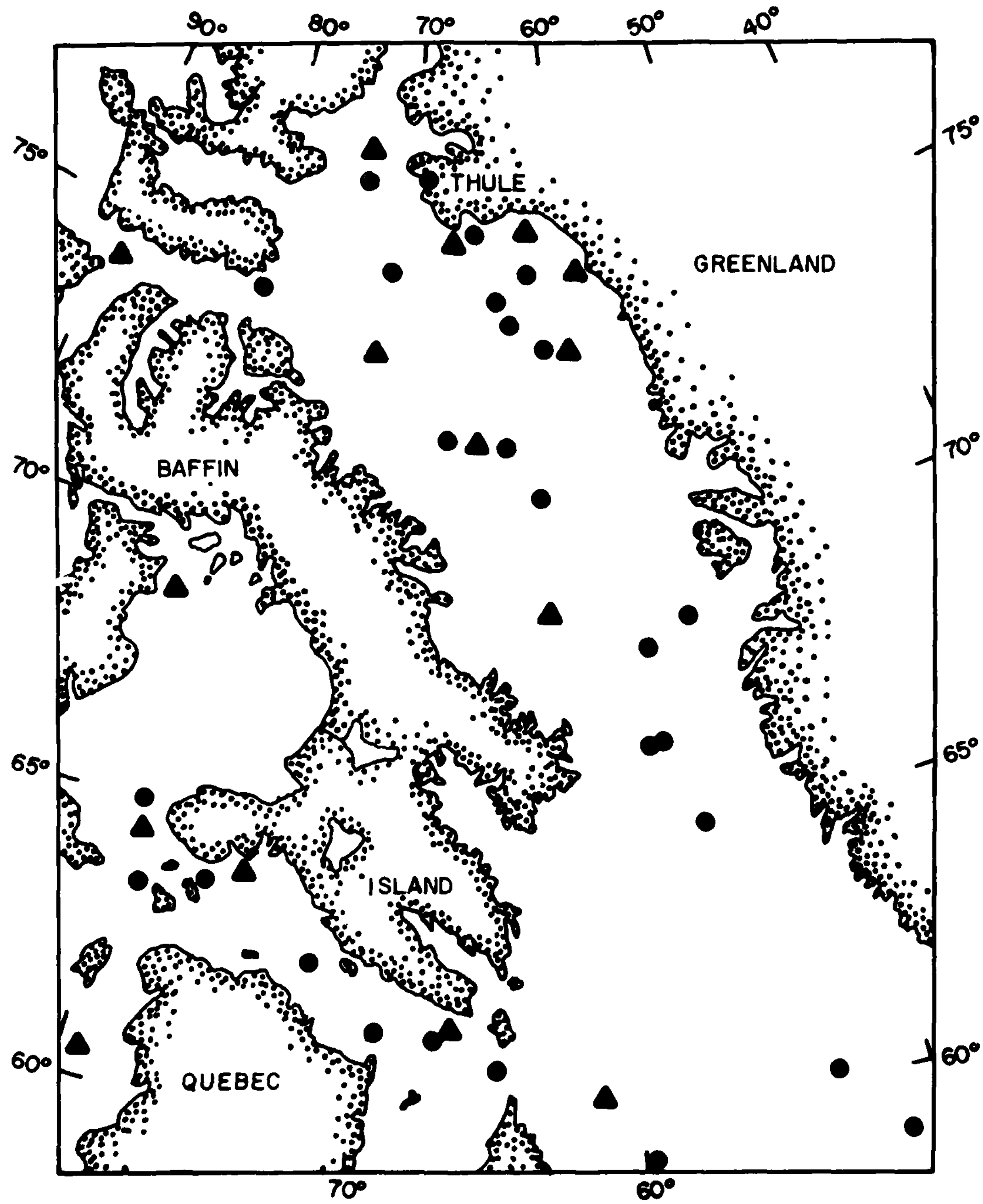

FIGURE 5: MAP OF SITES VISITED FOR AMBIENT NOISE MEASUREMENTS. DOTS ARE FOR SHIP BASED MEASUREMENTS. TRIANGLES REPRESENT AIR DROPPED SONOBUOY MEASUREMENTS.

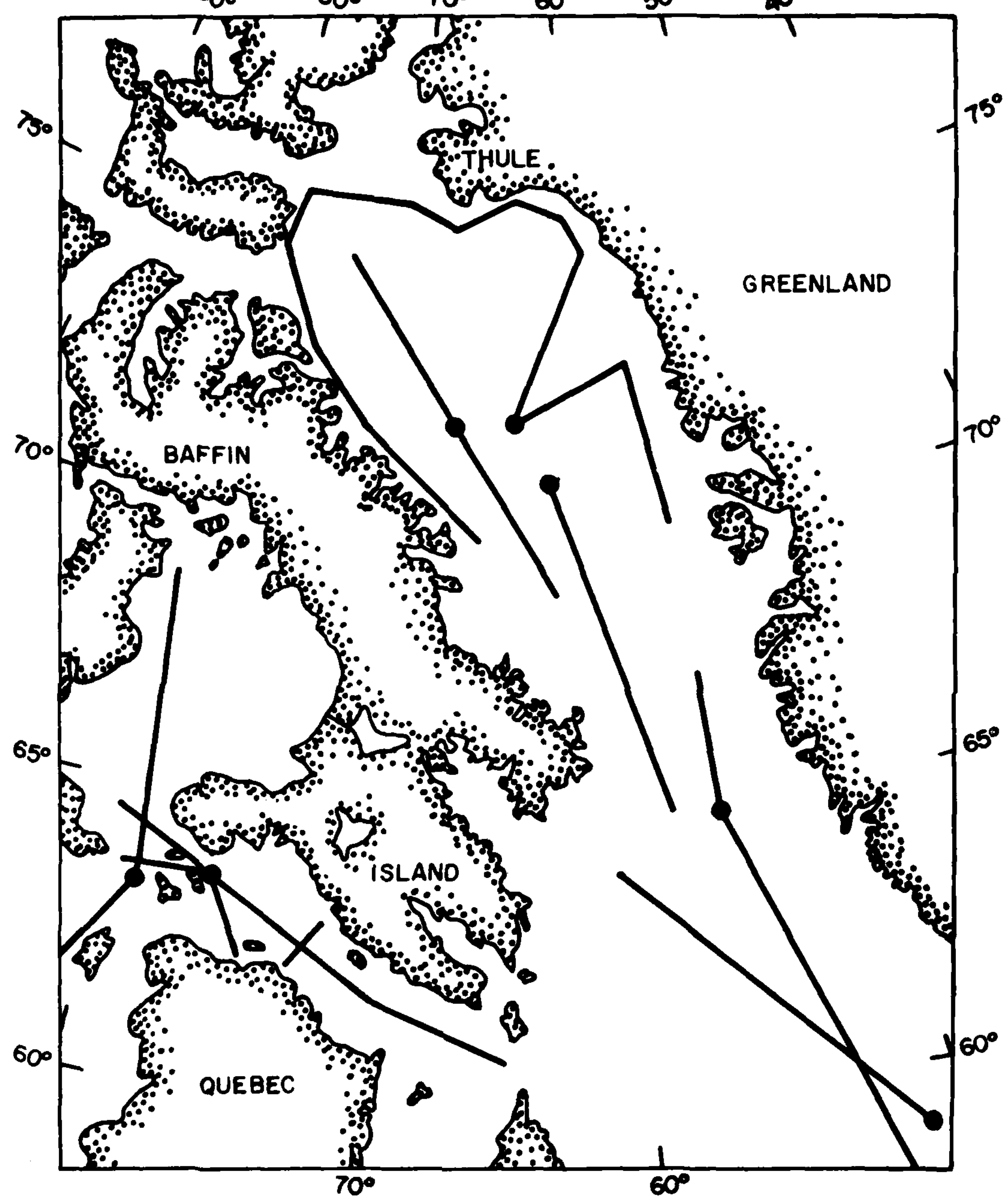

FIGURE 6: MAP OF SOUND PROPAGATION MEASUREMENTS. AIRCRAFT FOLLOWED TRACKS SHOWN WHILE DROPPING EXPLOSIVE SOUND SOURCES. SHIP LISTENED AT DOT ALONG LINE.

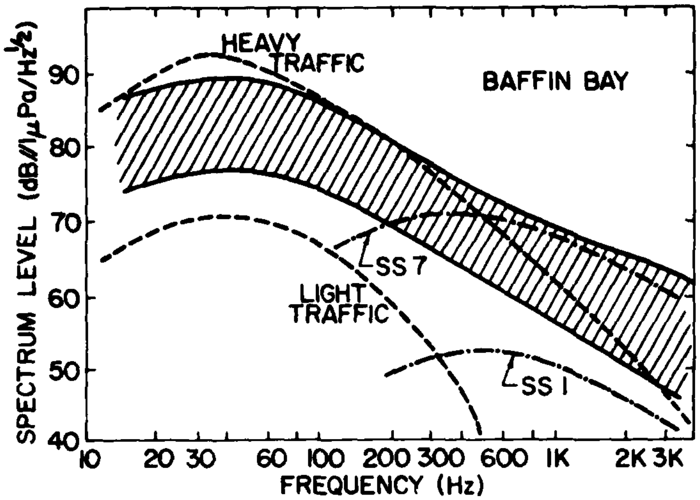

FIGURE 7: RANGE OF AVERAGE UNDERWATER NOISE SPECTRUM LEVEL OBSERVED IN BAFFIN BAY (SUMMER 1972, 1973)

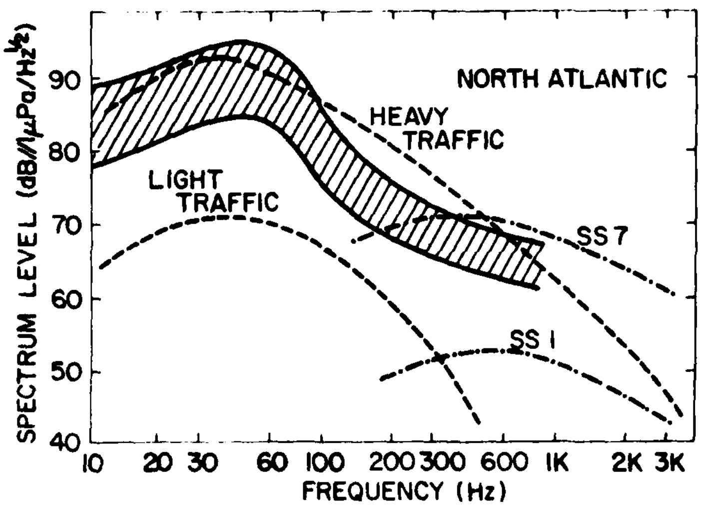

FIGURE 8: RANGE OF AVERAGE UNDERWATER NOISE SPECTRUM LEVELS OBSERVED IN THE NORTH ATLANTIC (SUMMER 1977)

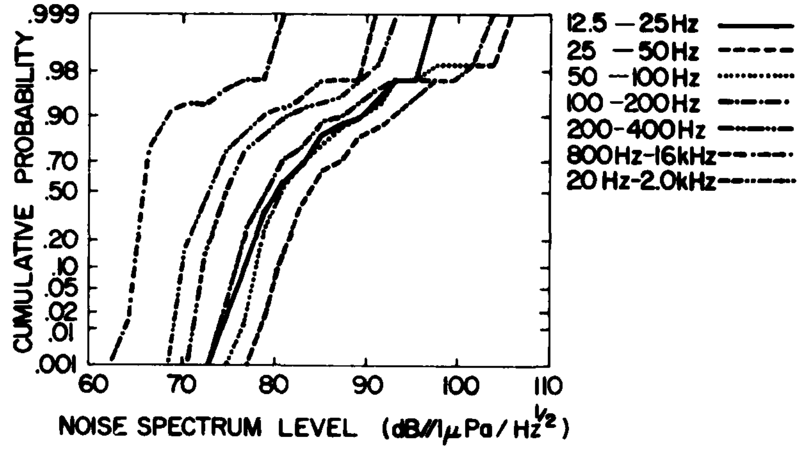

FIGURE 9: CUMULATIVE PROBABILITY DISTRIBUTIONS FOR UNDERWATER NOISE SPECTRUM LEVELS AT A LOCATION IN MELVILLE BAY (SUMMER 1973)

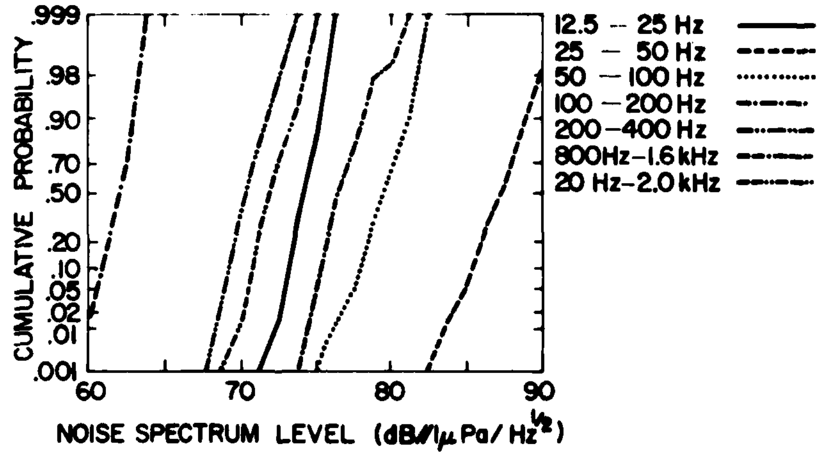

FIGURE 10: CUMULATIVE PROBABILITY DISTRIBUTIONS FOR UNDERWATER NOISE SPECTRUM LEVELS IN THE LABRADOR SEA (SUMMER 1973)

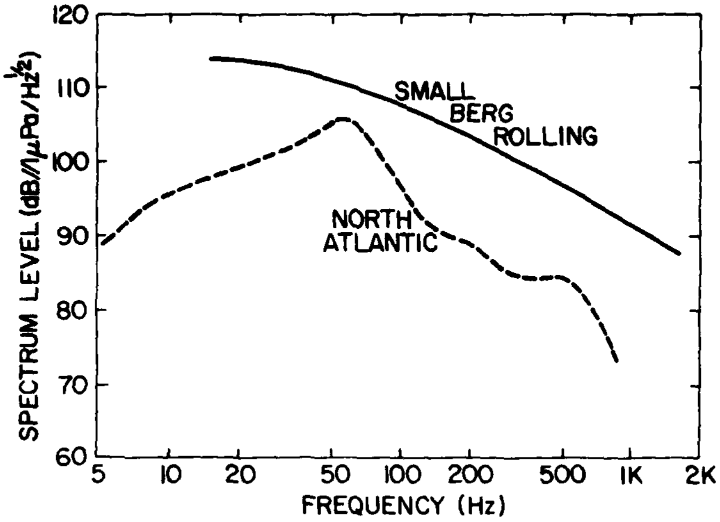

FIGURE 11: MAXIMUM UNDERWATER NOISE SPECTRUM LEVELS OBSERVED IN (SOLID LINE) BAFFIN BAY AND IN A (BROKEN LINE) IN THE NORTH ATLANTIC

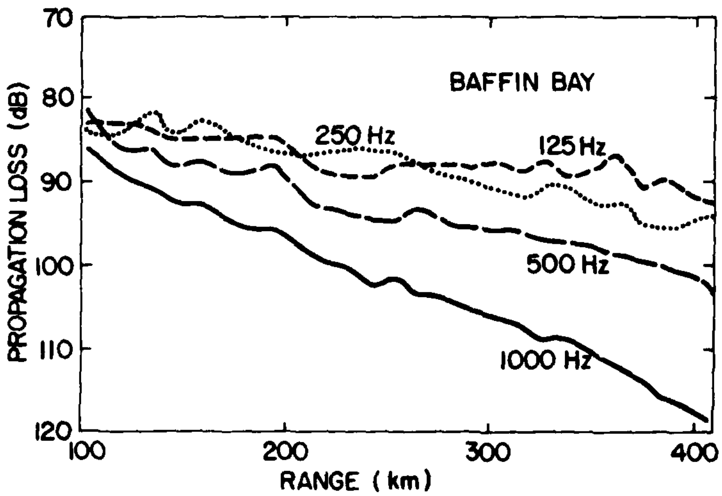

FIGURE 12: PROPAGATION LOSS VERSUS RANGE

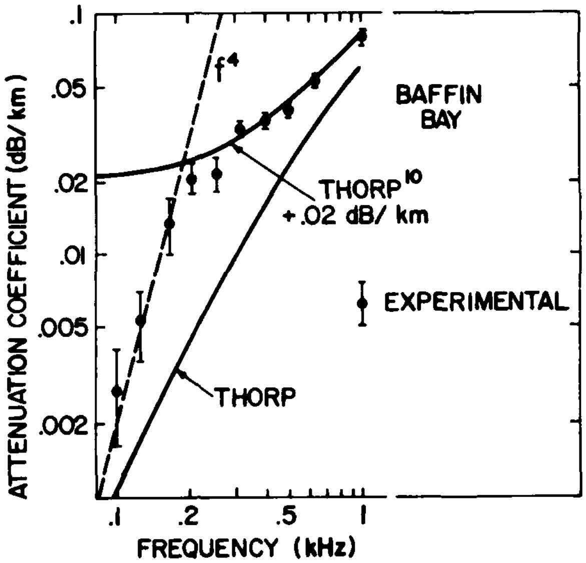

FIGURE 13: ATTENUATION COEFFICIENTS

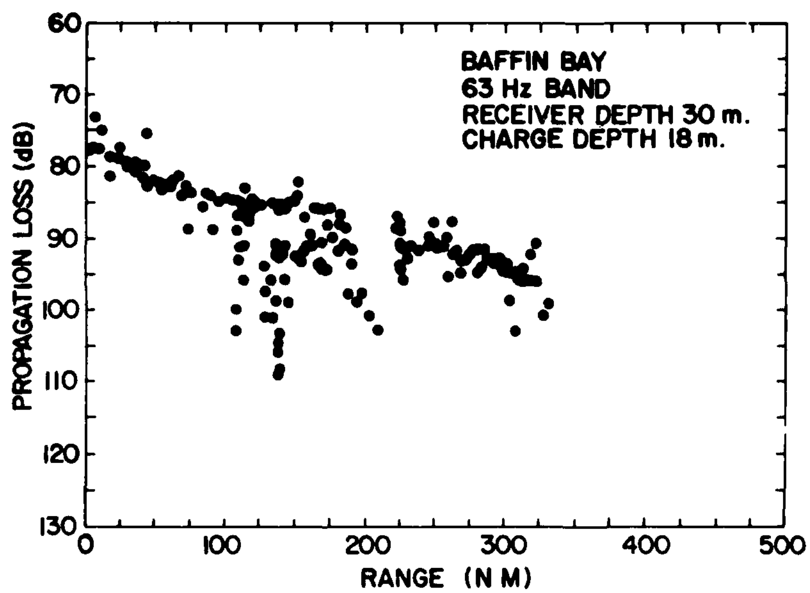

FIGURE 14: UNDERWATER SOUND PROPAGATION LOSS AT 63 HZ IN BAFFIN BAY (SUMMER 1973)

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Large powerful liquid natural gas carriers may soon ply Arctic waters year round. Concern has been expressed over the impact the resulting noise will have on Arctic marine life. This study includes estimates of LNG carrier radiated noise source levels and resulting sound levels at a given distance from the ship for a number of operating conditions. Measurements of sound propagation and ambient noise conditions in Baffin Bay are used to estimate the ship noise levels in relation to the summertime noise background.

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